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THE CORRELATION BETWEEN AIR-BORNE SALT AND CHLORIDES CUMULATED ON CONCRETE SURFACE IN THE MARINE ATMOSPHERE ZONE IN NORTH TAIWAN

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Key words: air-borne salt, chloride, effective precipitation, reinforcement concrete.

ABSTRACT

In this study, the improved Japanese salt sampler was adopted for the air-borne salt sampling tests in coastal areas of northern Taiwan. Thirty-five collection stations were set up in the northern coastal areas to collect air-borne salt data monthly from 2006 to 2009. As the exposure of structures in the natural environment, the chloride on the concrete surface of RC structures would be washed away by the precipitation. Therefore, a two-phase collection method was used to get the total air-borne salt "C_{air}" and the adhesive air-borne salt "C_{adh}". The statistic results showed that the percentage of C_{adh}/C_{air} has a high correlation with the volume of effective precipitation. Conclusively, the concentration of chloride ion on the concrete surface can be inferred a linear empirical formula according to the regional climatic characters to indicate the total air-borne salt and the adhesive air-borne salt on concrete surface respectively.

I. INTRODUCTION

Taiwan is located in subtropical area and surrounded by the sea, with hot and humid climate that is easy to cause corrosive environment inherently. In such atmospheric environment with high temperature, high humidity, and salt or harmful pollutants, whether the structure is constructed of reinforced concrete or steel has faced harsh environmental tests. Furthermore, the frequent earthquakes, typhoons, and the overrun usage of structures all make the cracks generated as well as accelerate the diffusion of corrosion factors. Domestically there are few statistic data to be applied as references for the effects on the structure corrosion that is caused by environmental characteristics and atmospheric conditions. Consequently it's difficult to practice the concept of durable anti-corrosion design. The corrosion of concrete structures in coastal areas is a common problem that can be found globally. It can result to a very serious impact to a country's economy. Therefore the corrosion issue of reinforced concrete structure under salty environment has been a very important issue in the international research on structural durability. However, the above-mentioned topics mostly focus on accelerating the tests to probe the damage caused by the chloride ion that adhesive to or penetrated into the concrete structure. Through the research on the mechanism, it's more explicit of the corrosion of reinforced concrete structure under salty environment, the environmental factors of the structures under salty environment are scarcely discussed. Most of the researches [7, 12] that are related to the sort of topics are on the basis of the tests from the laboratories. However, the conditions in the laboratories are not able to reflect the actual conditions. A small part of the researches [2] were conducted with on-the-site experiments. However, the sites were mostly set underwater or in intertidal zones. Researches on the ground structures that are exposed to the air-borne salt are few. All of the circumstances make it difficult to clearly and definitely draw up the possible effects by the air-borne salt when designing or evaluating the anti-corrosion structures for each region.

Just like the earthquakes normally occur in seismic belts, the corrosion of reinforce concrete structures is also geographic-dependent. If we can have a better control of all the environmental factors just like what we have done for seismic design, we will not only be able to design and evaluate the

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structure more accurately, but also estimate the life-cycle cost of the structure correctly. It can also help to come up with a more effective policy to prevent the corrosion of reinforce concrete structures depending on the regional conditions, in order to minimize the maintenance costs.

For these reasons, the study is initiated to investigate the regional air-borne salt environments at the coastal areas in northern Taiwan, to sample the concrete from old structures on the spots and analyze the chloride content on the surface.

II. LITERATURE REVIEW

The mechanism of air-borne salt transportation is the phenomenon of the seawater moisture from splashed sea waves being carried to the land by the wind. The salt in the moisture, therefore, becomes the air-borne salt. The concentration of air-borne salt is closely related to the wind speed as wind with higher speed may carry more salt to a longer distance. Therefore the role of the wind is important in this effect. When the wind speed increases, there may be measured higher concentrations of air-borne salt with the same distance. The effect declines as the increasing of the distance away from the coastline. This is because that the larger the granules are, the less quantity it can be brought in due to the weight effect. The results are showed as reference [10]. The chloride concentration is highly correlated with the distances away from the coastline. When the concrete structures are 100 meters away from the coastline, the chloride concentration on the structure is about 70% less.

The Building Authority of Japan [1] investigated this effect with a 3-year period on 34 sites. With the data collected in the period, they have inferred a formula with the average value of total air-borne salt "C_{air}" and the declined distance according to the following assumptions.

1. Only the meteorological data retrieved in the locations near the investigating sites is considered. The geographical differences between the investigating sites and the observing locations of meteorological data, such as height, distances away from the coastline, are not considered.
2. The below-list secondary factors which could impact the amount of air-borne salt are not considered: the conditions of coastline (such as the differences between sandy shore and rocky shore), topography, the number of typhoons that hit, if there're shelter structures around it, and the angle between concrete surface and the coastline.

A regression analysis was done using the retrieved meteorological data described in point 1. The below formula can be derived based on the amount of air-borne salt with decline of horizontal distances.

$$C_{air} = 1.29 \cdot r \cdot u^{0.386} \cdot d^{-0.952} \tag{1}$$

The "r" in the formula represents the sea wind-time ratio from the coastline within the area of two 45-degree sides; the "u" is the average wind speed (m/s) during the period of the air-borne salt investigation; and "d" is the distance (km) away from the shoreline.

By comparing the values calculated from the above formula and the measured values from the literature references, and also considering the assumptions from point 2, the result showed that the variation coefficient of measured values and the calculated values is too large. So far we can only use it to prove the macroscopic characteristic of the decline of air-borne salt with increasing distance, but cannot modularize it. At the same time of measuring the amount of air-borne salt, some concrete specimens were set on the same sites for exposing tests, and a formula showed in (2) was inferred according to the correlation between the surface concentration of chloride ion "C_0" and the amount of air-borne salt "C_{air}".

$$C_{air} = 0.563 \cdot C_0^{0.948} \tag{2}$$

Literature [9] pointed out that the concentration of chloride ion on the concrete surface increases over time. It also has correlation with the concentration of air-borne salt, the temperature of the concrete, the binding intension of concrete and chloride ion (including the cement content, water-cement ratio, cementing materials, and the binding intension of cementing materials and chloride ion), humidity, and the direction of structure. The concentration of chloride ion on the concrete surface will not increase anymore after a long period of time and will remain at a stable value. Sorensen and Maahn [12] investigated the 15- to 20-year-old bridges in Denmark, and found that the concentration of effective surface chloride ion was around 0.12 to 0.77% of the concrete weight. DuraCrete [4] used the following formula to calculate the design value "C_s" of the concentration of chloride ion on the concrete surface.

$$C_s = A_{cs} \cdot (W/B) \cdot \gamma_{cs} \tag{3}$$

In the formula, the "A_{cs}" represents the regression parameters that describe the correlation between the concentration of surface chloride ion and the water-cement ratio; the "r_{cs}" is the partial coefficient of the concentration of surface chloride ion, which applies the amount of 1.70, 1.40, or 1.20 respectively according to the relative high, mid, or low level of repairing costs for the structure when the rebars are damaged by the corrosion.

American Life 365 [7] is of the opinion that the concentration of the surface chloride ion is the main driving force to transmit the chloride ion in the concrete. Structures in different regions and with different conditions of exposure will have different accumulation rate and maximum concentration of chloride ion. And the suggestion was made that the life of structure shall be estimated according to the real value from each region (if there is test data available for this region).

Table 1. The distances and angles for the air-borne salt samplers.

Area	Abbreviation	Number	Distance from the shore (m)	Angle (°)
Keelung NTOU	KN	2	45、448	30
Taipei Chin-Shan	CS	8	9、54、134、275、467、846、1365、2546	45
Taipei San-Chi	SC	2	21、418	355
Chu-wei Fishing Port	CW	9	11、39、88、330、495、648、912、2851、8469	315
Yong-An Fishing Port	YA	2	150、550	310
HsinChu Fishing Port	HC	2	15、267	300
Lung-Fong Fishing Port	LF	2	11、445	290
Pai-Sha-Tun Fishing Port	PST	8	3、48、80、157、317、526、1200、2753	270

In China, Hua-Nan Harbour exposure experiment station of the Guangzhou Si-Hang Engineering Institute has conducted an exposure test over 10 years [5]. The increasing rate of the concentration of surface chloride ion on normal cement concrete (W/C = 0.4) with 10-year age is about 0.0184% per year. It is suggested that the maximum concentration of the surface chloride ion shall be determined based on the long-term exposure test results. After the period of 10 years, the maximum concentration of the surface chloride ion can be deemed a stable value basically.

The commonly adopted experiment method regarding the deposition amount of air-borne salt is ASTM G140 wet candle method [3]. The device is composed of the wet candle that is made by a wick inserted into the bottle and joined the liquor in the bottle. The deposition amount of air-borne salt is measured using chemical analysis. This means is not exactly the same type as the method for chloride ion attached on the surface of concrete. In addition, in order to discuss the distribution status of air-borne salt at coastal areas in Japan, Japanese researchers have developed gauze method and air-borne salt capture method respectively, to collect the natural-fall salt from the air. The gauze method is a stipulated means by JIS Z 2382 [6]. The method uses a 10 cm-by-10 cm gauze that is clipped in a frame to screen the air-borne salt by the natural air convection. The air-borne salt capture method is developed by the Institute of Japan Civil Engineering [11], with a device that is made of stainless steel. The concept uses the steel-made collection panel to capture the air-borne salt that is brought in by the sea wind and adhered on the panel.

The reinforced concrete structures in coastal areas are mainly affected by the strength and direction of the sea wind. The air-borne salt is brought onto the land by the sea wind, adhere to the surface of concrete, and penetrate into the concrete. In natural environments, the air-borne salt that adhered to the surface would be reduced by the brushing effect from the rain. However, the results from the tests with gauze method and air-borne salt capture method both showed that the air-borne salt will gain with the increasing of precipitation, which is different from the status occurs on real structures. Moreover, the amount of air-borne salt that can be captured by the gauze method is limited, which also cause the inconvenience of frequent sampling. Therefore, in this study an improved method was adopted referring to the above-mentioned methods, in order to establish the relationship between the air-borne salt and the chloride ion on the surface of the concrete structures.

III. TEST FOR THE CONTENT OF THE AIR-BORNE SALT AND THE CHLORIDE ION ON THE SURFACE OF STRUCTURES

However, the distribution characteristics of air-borne salt dramatically differ under different environmental and geographical conditions. The formulas from foreign countries for forecasting the air-borne salt corrosion are not suitably applicable to domestic cases. Therefore, it is necessary to conduct local investigations in order to establish the distribution rules for local environment. The study mainly focuses on the air-borne salt capture tests and the sampling for the chloride ion on existing concrete surface in northern Taiwan, in order to learn more about the correlation between the distribution of air-borne salt and the concentration of the chloride ion on the surface of concrete.

1. Sampling Spots for Air-Borne Salt

The sampling sites for air-borne salt were selected on the basis of the shortest distance from the coastline, and were set in a line toward the land. The angle of samplers was set in parallel to the coastline. In this study, Taipei Chin-Shan, Taoyuan Chu-wei Fishing Port, and Miaoli Pai-Sha-Tun Fishing Port were selected. Eight sampling sites were set respectively in the range from the seaside to 3000 meters toward the land. In order to have the data collected from the sampling sites also available for the interpolation estimation for other regions, additional five locations were selected along the coastline for sampling site setting, which are Keelung NTOU, Taipei San-Chi, Taoyuan Yong-An Fishing Port, Hsinchu Nan-Liao Fishing Port, and Miaoli Lung-Fong Fishing Port. Two sampling sites were set in the five locations respectively. The sampler volume, distances, and the angle of samplers are shown in Table 1. Fig. 1 shows the locations where air-borne salt samplers were set.

2. Sampling Method for Air-Borne Salt

The sampler used in this study was improved from the Japanese air-borne salt sampler. The original Japanese

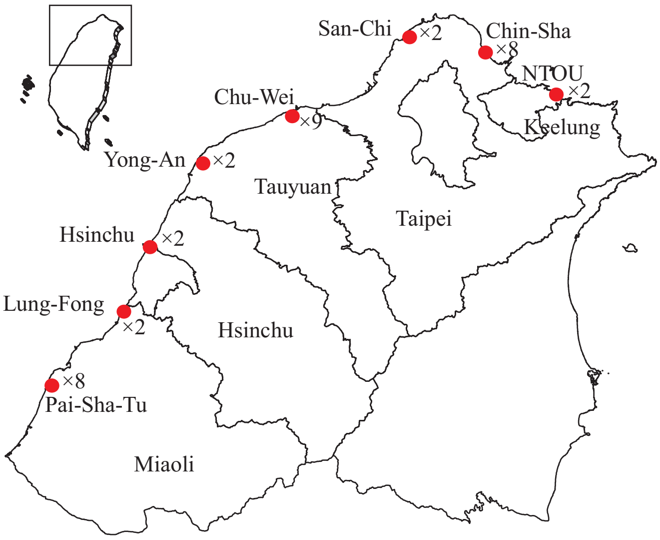

Fig. 1. Layout of air-borne salt measuring sites.

sampler has only one vent on the front panel. Considering the potential influence by the air resistance effect, another vent with same dimensions was made on the back panel in order to facilitate the natural convection, and consequently collect the air-borne salt in a more effective way. The improved air-borne salt sampler is shown in Fig. 2 and the on-spot installation status of sampler is shown in Fig. 3.

Moreover, since the Japanese sampling method does not take the rain brushing effect into consideration, the sampling process is made improved by adopting a two-phase sampling method. In the two phases, the total air-borne salt "C_{air}" (hereinafter referred to as total ABS) and the amount of adhesive air-borne salt under the rain brushing effect "C_{adh}" (hereinafter referred to as adhesive ABS) will be collected respectively. The detailed definitions of "total ABS" and "adhesive ABS" are explained further in the improved process of air-borne salt sampling.

(1) Before setting, use deionized water to clean the collecting panel, silica gel hoses, and the inside of the plastic container.
(2) When sampling, use deionized water to rinse the salt collected in the trough and silica gel hoses into the plastic container, then measure the weight of the water in the plastic container and retrieve the partial water sample A after fully stirring.
(3) Change the plastic container into a clean one, use deionized water to rinse the salt adhered on the collecting panel into the plastic container, then measure the weight of the water in the plastic container and retrieve the partial water sample B after fully stirring.
(4) Analyze the concentration of chloride on the retrieved water samples using CNS 14702 A3384 electronic-titration method, and calculate the amount of the air-borne salt using the following formula.

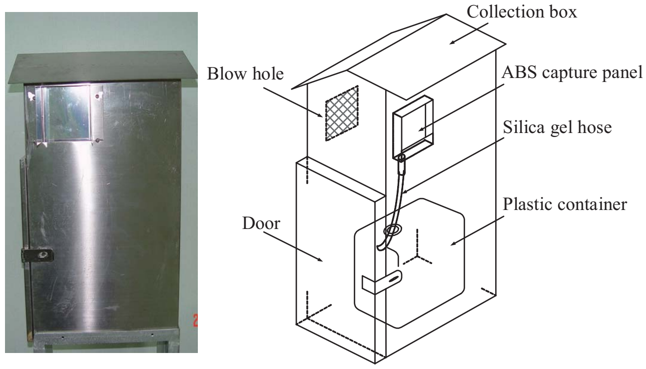

Fig. 2. The improved Japanese air-borne salt sampler.

Location: Chu-wei Fishing Port Location: Pai-Sha-Tun Fishing Port

Fig. 3. Installation of air-borne salt sampler.

$$ABS(mdd) = \frac{C \times W}{T \times A} \tag{4}$$

in which
C: the concentration (mg/ml);
W: the water content (ml)
T: the time (day)
A: the area (dm^2)
$mdd = 1mg/dm^2/day, 1dm^2 = 100cm^2$

(5) The amount of air-borne salt that derives from analyzing the water sample B in step (3) using the analysis method in step (4) is "adhesive ABS C_{adh}"; the "total ABS C_{air}" is the sum of the amount of air-borne salt derives from analyzing the water sample A in step (2) and water sample B in step (3).

The case of the air-borne salt sampler was made of stainless steel in principle, and the collecting panel is in 10 cm by 10 cm, which can be made of smooth materials such as stainless steel shell or acrylic. The sampling frequency was once a month.

3. The Concentration of Chloride Ion on the Surface of Structures

The concentration of chloride ion on the surface of structures "C_0" means the concentration of chloride ion cumulated in the range from the surface of the concrete to the depth of 0.5 cm. The C_0 is a significant parameter of the formula for chloride diffusion. An investigation conducted by Thomas

Table 2. Information on sampling structures.

Item	Location	Structure	Sampling spot	Date of construction	Distance (m)	Age (year)
1	Pai-Sha-Tun	Bridge	Deck	1975.01	335	35
2	Pai-Sha-Tun	Road	Barrier	-	516	-
3	Wai-Pu	Bridge	Beam	-	25	-
4	Lung-Fong	Channel	Channel	-	445	-
5	Lung-Fong	Bridge	Deck	-	445	-
6	Yong-An	Bridge	Beam	1990.07	70	20
7	Yong-An	Bridge	Beam	1990.07	190	20
8	Yong-An	Bridge	Beam	1983.03	340	27
9	Guang-Yin	Bridge	Deck	-	460	-
10	San-Chi	Bridge	Deck	1991.04	260	19
11	San-Chi	Building	Column	1980.12	22	30
12	San-Chi	Building	Column	1980.12	10	30
13	San-Chi	Bridge	Abutment	1991.04	10	19
14	Chin-Shan	Bridge	Barrier	1982.08	25	28
15	Chin-Shan	Bridge	Deck	1982.08	25	28
16	Chin-Shan	Bridge	Abutment	-	240	-
17	Keelung	Building	Column	-	570	>20

Note: "-" means no information was available.

[14] and several researchers showed that the chloride ion still keeps gaining on the surface of concrete specimens that have been exposed on tidal zone for four years. Although in this study the large concrete specimens have been exposed for testing purpose for more than 3 years, the accumulated amount of the surface chloride ion still haven't reached the ultimate saturation due to the slow accumulative rate under the exposure in the air. Therefore it's still unable to establish the correlation between the concentration of the surface chloride ion and the air-borne salt via the short-age specimens. It wsa also found that the empirical formulas from foreign countries are quite different from region to region, and it also can't be sure if they are applicable to the environment in Taiwan. Therefore, in order to accurately establish the domestic formulas for the correlation between the concentration of the chloride ion "C_0" on the concrete surface and the air-borne salt, it's necessary to select old structures that are more than 20 years old in the vicinity of the air-borne salt samplers, and to collect the concrete powder from the surface to the depth of 0.5 cm for further analysis on the concentration of the surface chloride ion. The locations, sampling spots, dates of construction, and the distances (away from the coastline) of the sampling structures are shown in Table 2. Most of the sampling structures were more than 20 years old, but the construction dates of some structures are not available.

IV. RESULTS AND DISCUSSION

1. Weather Data Analysis

Weather data are treated as a key factor that can affect the amount of air-borne salt with the interaction of different wind directions, wind speeds, and precipitation. Weather records used in this study were obtained from the Central Weather Bureau and the Environmental Protection Administration respectively. The data cover all the sampling locations that include data from Keelung, Dayuan, Guangyin, Hsinchu, and Miaoli air quality monitoring stations, as well as Chinshan, Tamsui, and Chunan weather stations.

Since the installation of air-borne salt sampler is with certain direction requirement, the wind direction, speed, or precipitation would not necessarily affect the sampling in all cases. Therefore in this study the relationship between the wind directions and the installation directions of air-borne salt samplers will be considered and modified when taking the weather data into account. Firstly, the data of wind direction were analyzed to acquire the effective ratio of the wind direction to the sampler, which is the percentage of the samedirection rate between the hourly wind direction and the sampler. The modified formula is shown as Eq. (5). Afterward, analyze the wind speed and precipitation data by comparing the wind direction at that time, and modify the angle of the sampler following the analysis results. In this way the adopted assumption is that the wind speed and precipitation only affect the sampling of air-borne salt when they are within the range of 180°. The modified wind speed and precipitation are effective wind speed and effective precipitation, and the modified formulas are shown as Eqs. (6) and (7).

Modified effective wind direction:

$$r = \frac{\sum_{j=1}^{30}\sum_{i=1}^{24}\cos(\beta_{ji} - \alpha_{ji})}{j \times i} \times 100\% \quad \text{unit} : \% \tag{5}$$

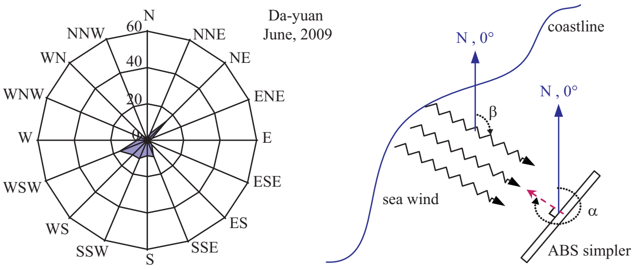

Fig. 4. The diagram of the transformed weather parameters.

Modified effective wind speed:

$$u_r = \frac{\sum_{j=1}^{30}\sum_{i=1}^{24} u_{ji} \times \cos(\beta_{ji} - \alpha_{ji})}{j \times i} \quad \text{unit}: m/sec \tag{6}$$

Modified effective precipitation:

$$w_r = \sum_{j=1}^{30}\sum_{i=1}^{24} w_{ji} \times \cos(\beta_{ji} - \alpha_{ji}) \quad \text{unit}: mm \tag{7}$$

In which
α: the angle of sampler;
β: the wind direction angle according to the Weather Bureau;
u_{ji}: the original hourly wind speed provided by the Weather Bureau (m/sec);
w_{ji}: the original hourly precipitation provided by the Weather Bureau (mm);
i: the number of hours;
j: the number of days;

Take the example of the data of Taoyuan Chu-wei fishing port in June, 2009. The weather data adopted were retrieved from the Da-yuan weather observation station. The percentage of each direction is shown as Fig. 4. It is the distribution of the accumulated percentage of daily and hourly wind speed for each direction. In this location, the sampler is installed in the direction of 315°, therefore only the wind direction within the range of northeast (turning counter-clockwise) to southwest will be effective to the sampler. The angles of hourly wind direction were used to calculate the effective wind directions with Eq. (5). If the value is negative, then it's taken as 0. The cumulative value of the data from the 30 days in June at total 720 hours showed that the effective wind direction was 22.5%. The percentages of the effective wind direction for each month from 2007 to 2010 are shown in Table 3.

The calculation of the effective wind speed is similar to the way that the effective precipitation is calculated. Take the example of the data of Taoyuan Chu-wei fishing port for June, 4, 2009 to calculate the effective precipitation. The angles of hourly wind direction and hourly precipitation are shown in Table 4. The values in Table 4 can be applied to Eq. (7) to sum up the effective precipitation for that day to be

Table 3. The monthly percentage of the effective wind direction in Taoyuan Chu-wei fishing port from 2007 to 2010.

Month \ Year	2007	2008	2009	2010
January	9.9	6.7	16.5	10.4
February	13.1	8.2	11.9	12.4
March	13.9	13.6	10.9	11.8
April	15.9	15.5	10.8	10.8
May	23.9	12.9	13.8	-
June	26.6	20.5	22.5	-
July	23.0	19.0	24.2	-
August	16.4	30.8	21.9	-
September	14.2	12.2	7.6	-
October	2.1	8.2	4.4	-
November	2.3	7.6	5.7	-
December	6.7	6.1	5.6	-

unit: %

Table 4. The effective precipitation of Taoyuan Chu-Wei fishing port for June 4, 2009.

Time (hour)	Wind direction α (°)	Precipitation (mm)	$w \times \cos(\beta-\alpha)$
1	312	0	0
2	59	0	0
3	33	0.4	0.08
4	96	20	0
5	67	2.8	0
6	210	22	0
7	183	18	0
8	133	3.2	0
9	175	0.8	0
10	176	2	0
11	297	1.8	1.71
12	37	5.4	0.75
13	39	1.4	0.15
14	47	12	0
15	41	2.2	0.15
16	157	2.2	0
17	273	6.8	5.05
18	46	5.4	0
19	49	0.8	0
20	71	0.2	0
21	111	0	0
22	36	6.6	1.03
23	109	5.8	0
24	124	0	0

unit: *mm*

8.9 mm, which is significantly different with the real total precipitation on that day. If we use the average effective wind direction of 14.0% and the total precipitation on that day to calculate the effective precipitation, we get the value of 16.8 mm, which still has a nearly one-fold difference compared to the precipitation value calculated from hourly data.

Table 5. The test results of the total air-borne salt on the coastal spots of each area.

Season \ Area	KN	CS	SC	CW	YA	HC	LF	PST
2006 winter	3.48	12.38	7.98	4.13	0.27	0.29	0.36	0.66
2007 spring	1.88	5.75	3.34	1.37	0.85	0.88	0.49	0.96
2007 summer	0.72	1.19	0.30	0.07	1.32	0.97	0.62	1.81
2007 autumn	5.93	23.42	16.58	6.83	4.60	1.96	1.09	5.77
2007 winter	3.77	15.58	5.86	5.69	0.57	0.69	0.19	0.97
2008 spring	1.02	3.05	0.89	1.46	0.70	0.58	0.32	0.92
2008 summer	0.80	0.29	0.47	0.27	1.07	1.14	0.70	4.13
2008 autumn	5.50	22.99	2.51	5.67	0.18	0.25	1.24	3.54
2008 winter	4.41	16.33	7.12	4.68	0.63	0.68	0.22	0.60
2009 spring	2.25	4.08	0.79	2.04	0.27	0.25	0.17	0.73
2009 summer	0.47	0.30	0.50	0.23	2.06	1.65	1.17	2.84
2009 autumn	4.36	25.04	4.09	5.43	0.81	0.96	1.43	1.99
2009 winter	4.45	11.89	3.29	4.36	0.98	0.94	0.47	1.50

Note: The unit for total ABS is *mdd*; the seasonal data derive from the average of three months.

Therefore, in this study, the accumulated hourly effective precipitation and effective wind speed in a month will be applied as parameters for analysis.

2. The Results of Air-Borne Salt Sampling and Testing

From December 2006 to February 2010, there were 39 investigations of air-borne salt sampling finished. Table 5 shows the testing results of the locations that selected from coastal areas. From the diagrams, it is found the trend that the distribution of the air-borne salt changes with different seasons. Even it's in a small area from Miaoli to Keelung, the distribution characteristics of total air-borne salt were still quite different, and the seasonal effects will be different also. In all regions the total air-borne salt reaches its high in autumn (September, October, and November). It's mainly affected by the frequent typhoons in autumn. However, in the area from Keelung to Chu-wei, the total air-borne salt in winter (December, January, and February) is much more than the total air-borne salt in spring (March, April, and May) as well as summer (June, July, and August). It is supposed to be subject to the effects of the northeast monsoon in winter. As for the area from Chu-wei to Miaoli, the total ABS in spring and summer are both higher than it is in winter, which is affected by the southwest monsoon. Therefore, the distribution trend changes with the shift of directions of monsoon. In addition, the seasonal distribution statuses of the total ABS in every sampling locations list in Fig. 5 mostly shows a considerably high reproducibility, which means the values of total ABS in every seasons are quite close as well as indicates that the investigation conclusions in this study are highly referable.

Fig. 6 shows the curve of the seasonal distribution of the total ABS at Chin-Shan area. It can be found from the figure that there are significant differences of the total ABS in different seasons. The total ABS in autumn and winter is much higher than it is in spring and summer, in which the differences can be decuples. Moreover, the amount of total ABS is also relevant to the distance away from the coastline. The amount of total ABS collected from each sampling sites declines as the distance gains. When the distance away from the coastline is more than 500 m, the amount of total ASB in each season declines to only 13% to 28% of the amount collected on coastal sites. And when the distance away from the coastline is more than 1200 m, the amount of total ABS approximates to a stable and relatively small value. The same trend is also found in other regions in this study.

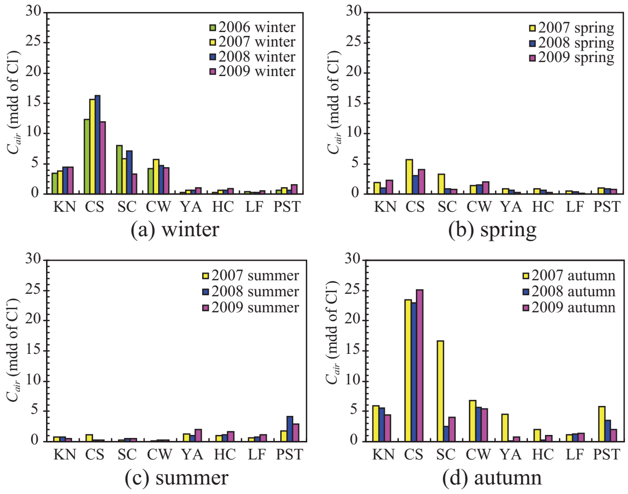

Fig. 5. The seasonal distribution of the total ABS on the coastal spots of each area.

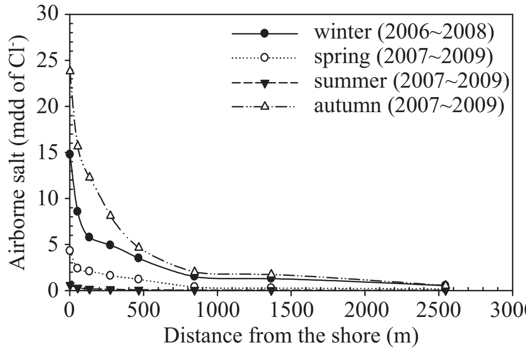

Fig. 6. The seasonal distribution of the total ABS at Chin-Shan (Taipei).

Fig. 7 shows the annual distribution of the average total ABC "$C_{air,year}$" and adhesive ABS "$C_{adh,year}$" in the sampling areas, with the data collected from June 2008 to February 2010. From the bar chart it can be found that the amount of the adhesive ABS collected in Keelung (KN), Chin-shan (CS), and San-chi (SC) areas was around 1.9 to 11.1% of the amount of total ABS, among which the largest difference is seen in CS area, with a significant higher amount of air-borne salt than other areas. For the other five areas, the amount of the adhesive ABS was around 22.6 to 73.5% of the amount of total ABS. All of these indicate that the amount of air-borne

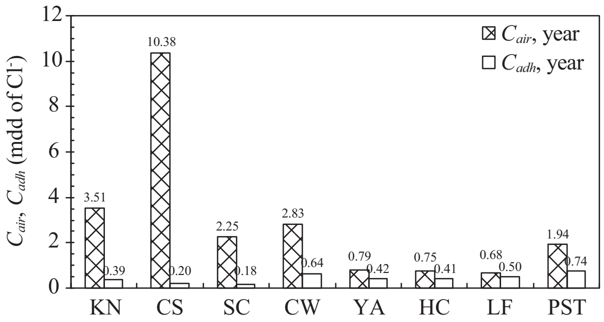

Fig. 7. The annual distribution of the average total ABS and adhesive ABS.

salt are obvious different under different levels of rain brushing in different areas. However, the differences (around 0.18 to 0.74 *mdd*) of the adhesive ABS from different areas are slight. The amount of the adhesive ABS in CS area was even lower than the other areas, which means the amount of the adhesive ABS does not necessarily increase with the amount of total ABC. There are other factors that need to be considered.

3. The Relationship between the Precipitation and the Air-Borne Salt

Table 6 shows the statistics of the average monthly precipitation and effective precipitation from December 2006 to March 2010 in sampling areas. The average monthly precipitation in all areas is higher than 139 mm. But only in Keelung, Chin-shan and San-chi areas, the average monthly effective precipitation was higher than 100 mm. The effective precipitation in other areas was 21 to 49 mm only. The statistics show that there is not necessarily a positive correlation between the effective precipitation and total precipitation. The effective wind direction also needs to be considered at the same time. Moreover, in Keelung, Chin-shan and San-chi areas, there were more than 50% of the months that were with the average effective precipitation more than 100 mm, while the ones in other areas were less than 20%. All of these indicate that the more the months that are with higher effective precipitation and exceed 100 mm in an area, the less the percentage of adhesive ABS in total ABS will be found.

In order to further discuss the correlation between the effective precipitation and the amount of the adhesive ABS collected by the sampler, a detailed comparison was done with the values of the monthly adhesive ABS and effective precipitation collected in the investigation. Fig. 8 shows the percentage of C_{adh}/C_{air} of Chin-shan area, and the distribution chart of the monthly effective precipitation in that area. It can be found from the chart that when the effective precipitation is higher than 100 mm, the adhesive ABS is less than 20% (except for the value in June 2008). It means that the higher precipitation does have more significant effect of brushing. Fig. 9 shows the percentage of C_{adh}/C_{air}, as well as the distribution of monthly effective precipitation in Keelung area. When the effective precipitation is less than 100 mm, the adhesive ABS is higher than 20% (except for the value in August and December 2009). Fig. 10 shows the percentage of C_{adh}/C_{air}, as well as the distribution of monthly effective precipitation in Pai-Sha-Tun area of Miaoli. From this figure the same trend can also be seen that when the effective precipitation is higher than 100 mm (July and October 2008, and August 2009), the adhesive ABS is less than 20%. Except for the effective precipitation of 5 mm in November 2009 when the adhesive ABS is less than 20%, 95% of the months

Table 6. The comparison chart of monthly average precipitation and monthly average effective precipitation.

Area	monthly average precipitation	monthly average eff. precipitation	Percentages of months with eff. precipitation > 100 mm
KN	335	133	65.0%
CS	253	148	72.5%
SC	175	103	52.5%
CW	154	21	2.5%
YA	147	22	2.5%
HC	142	21	10.0%
LF	139	27	15.0%
PST	148	49	20.0%

Note: The data are collected from December 2006 to March 2010, totally 40 months.

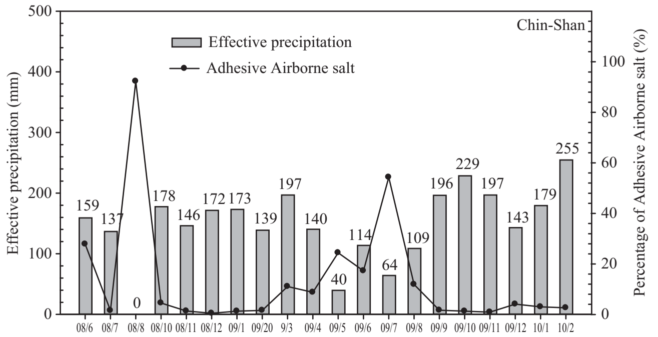

Fig. 8. The distribution of the monthly effective precipitation and the percentage of the adhesive ABS to total ABS in Chin-Shan area.

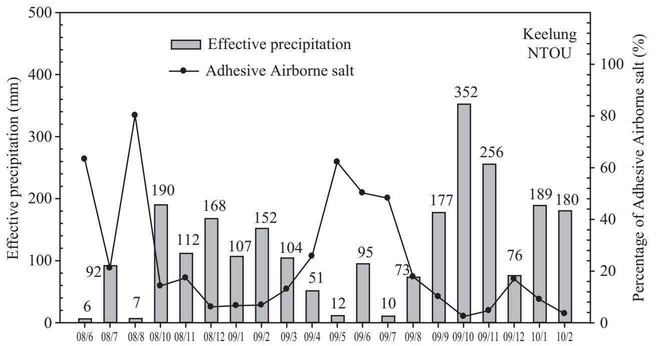

Fig. 9. The distribution of the monthly effective precipitation and the percentage of the adhesive ABS to total ABS in Keelung area.

Table 7. The test result of the chloride ion on the surface of concrete and the corresponding amount of ABS.

Item	Location	Structure	Cl^- on the surface (%)	Total ABS (*mdd*)	Adhesive ABS (*mdd*)
1	Pai-Sha-Tun	Bridge	0.4130	0.80	0.26
2	Pai-Sha-Tun	Road	0.1536	0.21	0.09
3	Wai-Pu fishing port	Bridge	1.0235	2.34	0.73
4	Lung-Fong fishing port	Channel	0.1824	0.19	0.07
5	Lung-Fong fishing port	Bridge	0.1921	0.19	0.07
6	Yong-An	Bridge	0.4992	1.24	0.27
7	Yong-An	Bridge	0.3765	0.90	0.20
8	Yong-An	Bridge	0.2481	0.61	0.15
9	Guang-Yin	Bridge	0.1470	0.33	0.14
10	Taipei San-Chi	Bridge	0.0929	1.89	0.10
11	Taipei San-Chi	Building	0.2333	4.63	0.15
12	Taipei San-Chi	Building	0.1815	4.63	0.15
13	Taipei San-Chi	Bridge	0.6044	4.63	0.40
14	Taipei Chin-Shan	Bridge	0.2519	6.91	0.17
15	Taipei Chin-Shan	Bridge	0.1910	6.91	0.17
16	Taipei Chin-Shan	Bridge	0.2385	4.05	0.12
17	Keelung	Building	0.2095	1.43	0.26

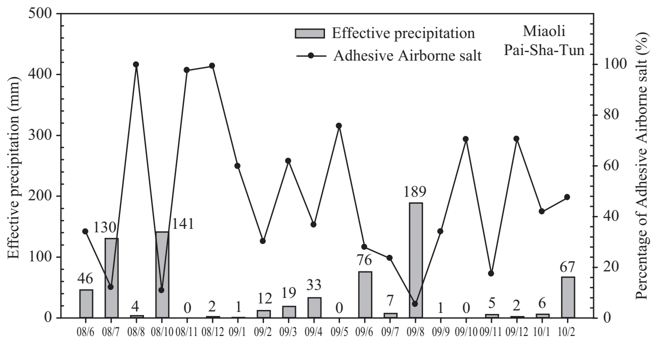

Fig. 10. The distribution of the monthly effective precipitation and the percentage of the adhesive ABS to total ABS in Miaoli area.

are in compliance with the above conditions. In addition, it can be found from the distribution chart of the effective precipitation of Pai-Sha-Tun area that the months with the effective precipitation more than 100 mm are relative fewer and mainly occurred in typhoon season of the summer.

From the above discussion of phenomena, the amount of the adhesive ABS is mainly affected by the brushing effect of the effective precipitation. When the total precipitation is high but the effective wind direction is different, the value of effective precipitation is not necessarily high. Consequently the brushing effect of the precipitation will not be significant. In this case, the total ABS that was collected via the air-borne salt sampler will be closer to the real behavior on the structures in such an area. As to the areas with monthly average effective precipitation higher than 100 mm, or more than 50% of the months in a year are with the effective precipitation higher than 100 mm, the total ABS cannot represent the real behavior. In that case, the chloride diffusion analysis should be on the basis of the amount of adhesive ABS instead.

4. The Relationship between the Concentration of Chloride ion on the Surface of Concrete and the Air-Borne Salt

Table 7 shows the test result of the concentration of the chloride ion on the surface of concrete, and the compiled data of the annual average of the total ABS and adhesive ABS corresponding to the location of structures. Fig. 11 shows the correlation between the total ABS and chloride ion on the surface of concrete. It can be found from the figure that the correlation seems to be low. However, considering the structures that exposed to the natural environments are subject to the rain brushing effect, the sampling results of the adhesive ABS were applied for further comparison. As it shows in Fig. 12, the amount of chloride ion on the surface of concrete and the adhesive ABS maintain a great linear correlation, with the coefficient of determination “R^2” at 0.907. From the result we knew that the brushing effect of the rain does affect the chloride content on the surface of concrete. From the above discussions, it could found that the effective precipitation is significant higher in North of the Taoyuan Chu-wei fishing port. It also means that the brushing effect is more serious in this region. So we only applied the sampling data of the chloride ion on the surface of concrete from the south of Chu-wei to be compared with the total ABS. As it shows in Fig. 13, the chloride content on the surface of concrete and the total ABS in the south of Chu-wei maintain a great linear correlation, with the coefficient of determination “R^2” at 0.949. All of these show that in the areas with monthly average effective precipitation less than 100 mm, or less than 20% of the months in a year are with the effective precipitation higher than 100 mm, the influence caused by the rain brushing effect is relative less. It also means the concentration of the chloride ion on the surface of concrete in such areas can be expressed via the

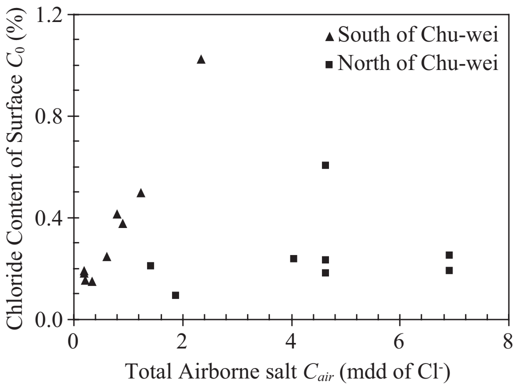

Fig. 11. The relationship between the C_0 and total ABS.

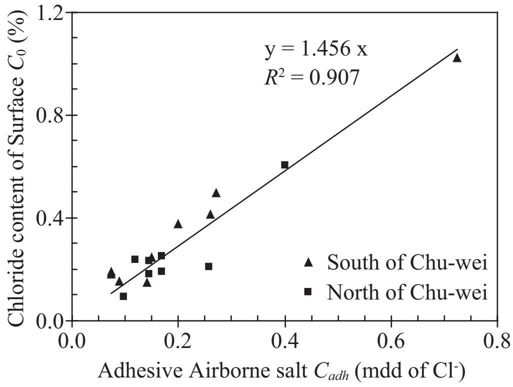

Fig. 12. The relationship between the C_0 and the adhesive ABS.

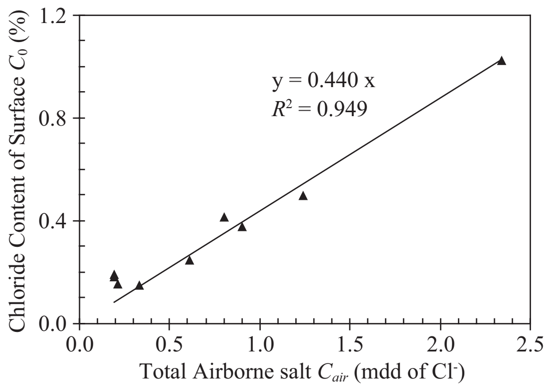

Fig. 13. The relationship between C_0 and total ABS in the south areas of Taoyuan Chu-wei.

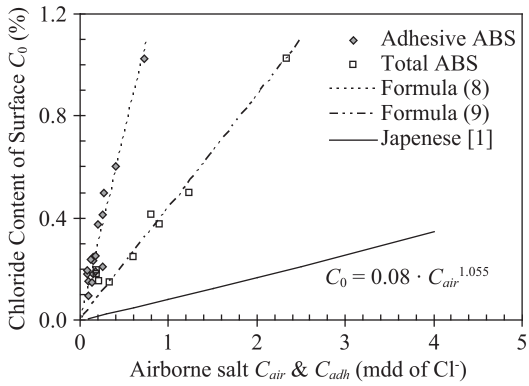

Fig. 14. The comparison of domestic and Japanese empirical formulas.

empirical formula for the amount of the adhesive ABS as well as the empirical formula for the amount of total ABS. The domestic empirical formulas derived from the regression analysis on the investigation are shown as below.

Empirical formula via regression using the amount of the adhesive ABS:

$$C_0 = 1.456 C_{adh} \quad (\%) \tag{8}$$

Empirical formula via regression using the amount of total ABS:

$$C_0 = 0.440 C_{air} \quad (\%) \tag{9}$$

There are many factors that could affect the concentration of the chloride ion on the surface of concrete, such as the concentration of air-borne salt, the temperature of concrete, cement content, water-cement ratio, the binding intension of cementing materials and chloride ion, and environmental humidity. However, the above results of analysis also show that under the environment in the coastal areas of northern Taiwan that is without much variation in temperature and humidity, the concentration of the chloride ion on the surface of concrete still can be estimated using the amount of total ABS or adhesive ABS, even when the other data (e.g. concrete mix proportions) are still unknown. The results show that the amount of the ABS is the primary factor that causes the chloride ion on the surface of concrete. As to the possible effects from the other factors, it still needs to be researched and discussed to be found.

From the literature review, we have learned that in various countries, most of the researches on the corrosion of concrete structures by the air-borne salt mainly focused on the analysis of aging behavior after the structures have been corroded by the chloride ion. The correlation between the corrosion and the concentration of air-borne salt were scarcely discussed. So far, only the Civil Engineering Research Institute of Japan has established an empirical formula to show the correlation between the concentration of the chloride ion on the surface of concrete and air-borne salt, as formula (2) showed. Compare this empirical formula with the two domestic empirical formulas established in this study, as shown in Fig. 14, the values that were derived from substituting the real-measured amount of total ABS into the formula are much smaller than the real-measured value of the concentration of surface chloride ion on concrete. The real-measured values are around 4 times larger than the calculated value. It shows that the empirical formulas from foreign countries do not applicable to the environments in Taiwan. Once they're misapplied, the concentration of surface chloride ion on the structures will be underestimated, which can result in the insufficiency of durability design, and seriously affect the safety and life of the structures.

V. CONCLUSIONS AND PROPOSITIONS

1. The results of on-the-site air-borne salt samplings and tests show that the distribution trends of the yearly amount of air-borne salt are about the same. Values collected from each region are with significant reproducibility, which means the samplers applied in this study is certainly applicable. The data from the tests also show that the amount of air-borne salt in the sampling regions is highly affected by the monsoon. The effect of the monsoon declines with the decreasing of the distance away from the coastline. When the distance is larger than 1.2 km, the air-borne salt will be relatively lower.
2. Since the air-borne salt is brought onto the land by the sea wind from the sea, it is highly direction-related. When the wind direction is not from the sea to the land, the effect will be little even if the wind speed or the precipitation is high. Therefore in this study, we discussed the correlations in terms of the effective wind direction, effective wind speed, and effective precipitation. It is also suggested to apply the hourly weather data for analysis, in order to establish the correlation between the weather data and the amount of air-borne salt.
3. By comparing the concentration of the chloride ion on the surface of the existing, old concrete structures with the adhesive ABS from the test results, a great linear correlation will be obtained, with the coefficient of determination at 0.907. The result shows that the brushing effect of the rain does affect the chloride content on the surface of concrete. It is also found in the south of Taoyuan Chu-wei that the chloride content on the surface of concrete and the total ABS maintain a great linear correlation, with the coefficient of determination at 0.949. These results show that in the areas with monthly average effective precipitation of less than 100 mm, the influence caused by the rain brushing effect is relative less. It also means the concentration of the surface chloride ion in such areas can be expressed via the domestic empirical formula for the adhesive ABS as well as the local empirical formula for the total ABS.
4. By correlating the percentage of C_{adh}/C_{air} and the percentage of the months with the effective precipitation higher than 100 mm in each area, we inferred that in the areas with monthly average effective precipitation higher than 100 mm, or more than 50% of the months in a year are with the effective precipitation higher than 100 mm, only the empirical formula (8) is applicable to the estimation of the chloride content on the concrete surface in these cases. However, in the areas with monthly average effective precipitation less than 100 mm, or less than 20% of the months in a year are with the effective precipitation higher than 100 mm, both the empirical formula (8) and (9) are applicable in these cases.
5. In this study, the foreign empirical formulas and domestic empirical formulas that used for the estimation of the surface chloride ion content with air-borne salt were compared. It was found that the values calculated with the foreign empirical formulas are far lower than the real-measured values, which means the foreign empirical formulas are not applicable to the domestic durability design to prevent the corrosion from the air-borne salt. As to the domestic empirical formulas that are recommended in this study, they are only applicable to the northern Taiwan. Applications for other regions need to be tested and verified prior to applying.

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